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CONCRETE COVER IN THIN-WALL REINFORCED CONCRETE FLOATING PIERS

By

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establishing a guide to fixing the minimum depth of concrete covering steel reinforcement in a floating pier or landing stage consisting of an assembly of precast concrete cells wherein the allowable maximum overall thickness of wall in any cell is restricted to 2 inches.

Based on the information developed in this study, it is concluded that a 5/8-in.-thick concrete cover is the minimum acceptable, provided that certain limitations are observed regarding composition of the concrete, size of the reinforcing steel, and application of protective coating to the reinforcement and the exterior of the floating structure.

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INTRODUCTION

Background

It is contemplated that small floating landing stages (for facilitating embarkation of personnel aboard small boats or debarkation therefrom) and comparatively large floating piers can be gainfully used by USN forces in any harbor. Such facilities conceivably consist of permanently joined assemblies of thin-wall precast reinforced concrete rectilinear cells. Reinforced concrete slabs, not thicker than 2 in. overall, constitute the bottoms, sides, and tops of the hollow structural units. Each floating assembly may be envisioned as being a compartmentalized concrete pontoon. A minimum depth of concrete covering steel reinforcement in the structural cells is desirable to minimize the weight factor. Exactly how thin depends on many variables, including quality of workmanship.

Objective

The aim of this study is to determine the minimum thickness of concrete over steel reinforcement, in thin-wall structural concrete not thicker than 2 in. overall, as an acceptable protection against corrosion of the embedded steel.

Literary Survey

This report is based on information developed by assessing the available technical literature dealing with concrete, either reinforced or prestressed or both, that is exposed to seawater. The survey covers pertinent papers published during the past 75 years. Analysis of the information so developed serves to delineate the facts established by previous investigators and to reveal whatever additional knowledge may be required for ensuring a reliable determination of minimum cover.

DURABILITY OF CONCRETE

General

The three fundamental factors influencing concrete durability are (1) resistance to weathering, (2) resistance to chemical attack, and (3) resistance to abrasion. The second factor involves, among other properties, watertightness. Note, however, that no concrete is absolutely impervious to the passage of moisture either in liquid or vapor phase. To ensure that the hardened concrete is as nonabsorptive as possible, the quality of the constituents and the proportioning, mixing, placing, and curing of the concrete require uniformity and excellent control at all times. A

reinforced concrete floating structure must be practically impervious to endure the destructive effects of the marine environment. Moreover, the concrete should be placed in one continuous operation, thus precluding any possible leakage through construction joints which would be present were placement not continuous.

Strength is not a measure of durable concrete although quality of the cement paste, quality of the aggregate, and denseness of the hardened concrete all contribute to strength.

Watertightness

It is an established fact that under proper organization, supervision, and inspection, concrete can be made practically impervious. Such accomplishment entails proper proportioning of suitable materials, and properly mixing, placing, and curing the concrete. Workmanship must be of the highest quality and equipment must be dependable. Producing watertight concrete necessitates constantly careful control of every operation. Seemingly insignificant mistakes can lead to an undesirable characteristic in the final product. Producing watertight concrete that has the necessary strength and durability is analagous to opening a combination dial-operated lock -- all operative factors must be correct to ensure the expected performance.

Lack of watertightness is usually associated with structural cracks and defective spots in otherwise good concrete. Discontinuities in the capillary system within the cement paste are among the physical characteristics that predetermine the watertightness of the cementitious matrix enveloping the particles of aggregate. The water/cement ratio (W/C) should be as low as practicable; the most effective means of enhancing watertightness of concrete, over and above correct compaction and workmanship, is minimizing the amount of water in the mixture.

Note that concrete having high density also has high unit weight, but may not be as impervious as a fully compacted concrete having lesser unit weight. All other factors considered equal, the lower the W/C, the lower the permeability of the concrete, and the lower the probability of the steel reinforcement corroding.

Salt Crystals

Continual evaporation of seawater spray and splash at those portions of the floating concrete pontoon above the water line can result in an accumulation of sodium chloride on the surfaces so exposed and also within any pores adjacent to the exposed surfaces of the slabs constituting the pontoon. The pressure developed by crystals growing within concrete subjected to seawater is explained as follows: "As sea water or any other salt solution evaporates, the point is reached where the water holds all the salt it can in solution, and beyond that point the excess is thrown out of solution, almost always forming crystals which continue to grow as evaporation proceeds. This should not result in any special damage, provided the crystals have plenty of room for growth, but the trouble is that they start to form not merely on the surface but back in

the pores. After a time, evaporation continues, these crystals often grow too large for their restricted habitations, and with the tremendous forces of crystal growth behind them, burst the walls which surround them. This type of disintegrating agency can most easily be prevented by adequately breaking capillary contact with the source of the moisture. ... In addition to evaporation of moisture, a temperature drop aids in crystal growth and is extremely important, although it appears to have escaped attention generally. A drop in temperature by reducing the solubility of salts often results in crystal growth in the interior of the wall. If the drop is considerable and if it occurs with proper velocity, comparatively large crystals may grow within the pores of the material and each single one acting like a tiny jack, produces a cumulative force which may be great enough to disrupt the whole structure. A conclusion has been drawn that this crystal pressure is very apt to be more important in the cold weather disintegration of concrete and other building materials, than even ice pressure itself."(1)*

Freezing and Thawing

A lucid explanation of how concrete disintegrates by alternately freezing and thawing is the following: "When concrete is subjected to freezing, the free water in its pores changes from a liquid to ice. Concrete in submerged condition has all of its pores filled with water which, upon freezing, changes into ice. Since ice occupies a considerably larger space than water, it will exert pressure on the walls of the minute water pores. As long as all pores are completely filled with water, as in the interior of submerged concrete, the pressure will be uniformly distributed and we have equal compressive stress in all directions, which, for homogeneous materials may be considered as a condition of no stress. The pores next to the surface are not subjected to this type of uniform stress condition except when the external pressure equals the internal ice pressure. ... The unequal ice pressure will produce tensile stresses in the walls of pores next to the surface of the specimens. Repeated freezings and thawings will thus set up repeated tensile stresses and the disintegration of the concrete may be considered at least partly as a condition of fatigue failure. The surface will disintegrate first and the progressive destruction will continue towards the interior of the concrete. The strength of the walls is determined by the strength of the cement paste as long as the same aggregate is used. For different aggregates the strength of the walls of the pores as well as the soundness of the aggregate will affect the resistance to freezing and thawing. Both the quality of the cement paste and the type of the aggregate therefore contribute to the resistance of the concrete to these destructive forces. Since the maximum effect of the freezing and thawing results when full pores are surrounded by empty pores, the water line is a particularly exposed place in all concrete structures partly submerged. Disintegration will therefore generally start at the water line and gradually spread out from this elevation. During the freezing of

* Underlined numbers in parentheses indicate reference numbers.

the specimens there is a differential in ice pressure from the surface of the concrete towards the interior as the freezing progresses gradually from the surface. Similarly a differential will occur when the specimen is being thawed and the transition from ice to water progresses from surface towards the interior. These differentials also contribute to the disintegration of the concrete, and the greater the differentials, that is, the greater the rate of freezing and thawing, the greater is the effect upon disintegration. Similar differentials will obtain if some of the pores in the interior of the concrete are only partially filled with water."(2)

For concrete having a W/C of 0.40 by wt (4½ gal per bag) and subject to a hydrostatic head of 1 ft, saturation to a depth of 2 in. occurs in about 5 years. In contrast, if the W/C is 0.58 by weight (6½ gal per bag), saturation to a depth of 1 in. occurs in about 1 year. Frost in a marine environment is the most severe exposure. Since fully saturated concrete cannot withstand freezing without disruption, it is vital that the aggregate be nonporous, the W/C be 0.40 (by weight) or less, and entrained air be present; in freezing climates the saturation is retarded if the concrete has low permeability, and in warm climates the rate at which embedded steel corrodes is reduced if the concrete permeability is low. Corrosion of reinforcing steel can, in principle, be obviated if moisture, chloride ions, and oxygen are excluded from the concrete cover. Chemical destruction of the hardened cement paste matrix by seawater is slow at low temperatures, but is comparatively rapid in the tropics; necessary resistance to such attack can be afforded only by low-permeability concrete incorporating portland cement low in tricalciumaluminate content (e.g., either ASTM Type II or V) and entrained air which decreases the rate of seawater penetration in warm climates and is a necessity in freezing climates. Though structural cracking is less likely in prestressed concrete than in reinforced concrete, the high tensile steel in the former is more susceptible to corrosion than the mild steel in the latter.(3)

Cement

A reasonably high cement content is an essential requirement for concrete exposed to seawater, whether above or below the water line.

The type of portland cement also is an important factor. Cements containing more than 8% tricalcium aluminate (C_3A) have poor resistance to magnesium sulfate which is present (averaging 3% by weight) in seawater. ASTM Type V portland cement contains an allowable maximum C_3A content of 5% by weight; Type II, an allowable maximum of 8% by weight. Type V portland cement obviously is more desirable in this respect than is Type II cement.(4)

Though ASTM Type II portland cement performs satisfactorily in seawater, either ASTM Type V or a pozzolanic cement is preferable for marine installations in tropical and semi-tropical regions. "In warm climates, such as the Mediterranean, or tropical climates, where chemical attack and crystallization caused by evaporation are dominant factors, the slag-containing and pozzolanic cements, or sulphate-resisting portland cement (e.g., ASTM Type V), are to be preferred; in this case experience indicates that the pozzolana can be treated as a substitution for up to

30 percent of the portland cement."(5) If the installations are in temperate and colder regions (severe winter climate), the pozzolana should be an addition to, and not a substitute for, the portland cement.

Aggregate

The permeability of the natural aggregate in the concrete is also a factor in the migration of chloride into hardened concrete. In a thin-wall reinforced concrete floating pier it is vital that the permeability of the aggregate particles approximate that of the encapsulating cement paste. The most desirable natural aggregate is trap rock which, under a constant hydrostatic pressure of about 3 atmospheres (about 43 psi), exhibits a permeability coefficient of 3.45×10^{-13} cm per sec which is comparable with the permeability coefficient for hardened cement paste that never has been allowed to dry, has a W/C of 0.38 by weight (4.3 gal per bag), and is subjected to the same hydrostatic pressure.(6)

Concrete incorporating ASTM Type II portland cement, fresh water, trap rock as coarse aggregate, and natural siliceous sand as fine aggregate, is considerably more resistant to 100 cycles of alternate freezing and thawing than is similar concrete incorporating gravel as coarse aggregate, all other things being equal.(7)

As long ago as 1917, the ACI in concert with the PCA recommended (5) that the maximum size of aggregate in concrete ships be ½ in.

Admixtures

Based on information in (8), an air-entraining admixture and an ASTM Type II portland cement should be used in concrete that is exposed to seawater and also subject to alternate freezing and thawing and alternate wetting and drying. The air-entraining agent aids in lowering the perviousness of the concrete.

Water-reducing admixtures have been successfully used in concrete exposed to seawater because less mixing water is required than if entrained air is used as the workability agent (9); thus, a less pervious concrete may be attainable for use in floating structures never exposed to alternate freezing and thawing. However, under freezing and thawing conditions, no water-reducing agent can ever be a satisfactory substitute for an air-entraining agent.

Another admixture that is effective for inhibiting corrosion of steel reinforcement is sodium benzoate when used at the rate of 2% (by weight) in the mixing water during production of the concrete or mortar. This admixture is known to remain in the hardened concrete for at least 5 years and also accelerates the strength of the concrete.(10)

The results to date of ongoing research in the Materials Science Division of CEL, in furtherance of the undertaking described in (11), indicate that polymer-cement-concrete may be advantageous wherever concrete structures are exposed to marine conditions. For a W/C of 0.50 by weight, using a cement factor of 5.9 bags (ASTM Type III) and 3/8 in. maximum size gravel, at various ages ranging to 1 year the compressive and tensile (in flexure and in splitting) strengths are 2 to 3 times the corresponding

strengths of conventional concrete, Young's modulus of elasticity is about 50% greater than that of conventional concrete, and water absorption is at least 67% less than that of conventional concrete if the liquid polymeric material (a latex admixture) concentration is 30 to 40% by weight of the cement. Though the test data developed to date are sufficient to serve as the basis for only a qualified endorsement of polymer-cement-concrete in preference to conventional concrete, a reliable endorsement can be expected within the next 5 years.

Porosity

The distribution of pore sizes is important relative to permeability. The median pore diameter in mortars cured in 68°F water for 14 days is between 0.04 and 0.1 micron (1 micron = 0.000039 in.); if cured in 68°F atmosphere at 50% RH, between 0.4 and 1.0 micron. In either case, variations in W/C and aggregate/cement ratio (A/C) do not produce important differences with regard to pore-size distribution. For a given slump, various degrees of compaction produce changes only in those pores greater than 5 microns in diameter.(12)

Permeability

"Permeability of the concrete cover is probably the most important factor, along with its quality, which influences the required thickness of the concrete cover for effective corrosion protection of the ... steel. ... Specifying minimum covers for corrosion protection without specifying the permeability of the concrete appears to be meaningless, since 1 in. of crack-free, dense concrete can offer complete protection, whereas 4 in. of pervious concrete cover still can be inadequate."(13)

"Cover of concrete over the steel ... is a factor which must be considered with permeability, for two inches of permeable concrete cover will yield less protection to steel than ... a quarter inch of impermeable concrete. However, when cover varies from point to point along a length of reinforcing steel where the concrete is of uniform quality, the result would be the same as if the cover were constant but the quality varied."(14)

A thin and dense cover thus offers more protection against corrosion of the steel than does a comparatively thick and permeable cover.

Curing

Curing at a constant temperature should be such that the newly cast concrete is continuously saturated with fresh water. Minimum permeability depends on the products of cement hydration filling the water-filled pores or capillaries among the cement gels composing the paste.(15)

As explained subsequently herein, the corrosion of reinforcement depends on the degree of penetration of seawater and its chlorides, carbon dioxide for decreasing the pH, and oxygen; porosity and rate of diffusion thus are important. Though chloride ions may be provided when the concrete

is later subjected to seawater, saturation of the concrete with fresh water during prolonged curing will prevent the diffusion of carbon dioxide and oxygen.

Cracking

Except during World Wars I and II when steel was in short supply, conventional reinforced concrete has not been an acceptable material in constructing sea-going vessels because of its tendency to crack at very low tensile stress developed during hogging, sagging, and rolling. Nevertheless, conventional reinforced concrete can be a useful structural material for floating piers in harbors because in such application the stresses are comparatively low, crack formation due to live loads can be controlled, and maintenance can be economical.

Shrinkage cracks as wide as 0.01 in. in reinforced concrete cannot be avoided, but are harmless provided the concrete is dense. Not only must the mix proportions and percent of entrained air be correct, but the freshly mixed concrete must be fully compacted to ensure sufficient density. Entrained air improves the resistance to moisture penetration and frost.(16)

In reinforced concrete structures exposed to seawater and to innumerable cycles of alternate wetting and drying, and additionally to cyclic freezing and thawing in wintry climates, the most common deterioration is the cracking and ultimate spalling of the concrete covering the corroding steel reinforcement. The higher the W/C, the larger the quantity of free water within the interior of the concrete, and the greater the deteriorative effects of cyclic wetting-drying and freezing-thawing.

In good concrete in waterfront structures under ordinary marine exposure, cracks appear 8 to 10 years after construction. Reduction and possibly prevention of cracking and subsequent spalling can be effected by using welded wire fabric or reinforcing bars of smaller diameter than usual or both. At the Port of San Francisco the thickness of concrete cover over steel reinforcement is at least three diameters of bar for exposure above the water line. The deck structure is considered most vulnerable to disintegration caused by corroding reinforcement.

The concrete cover simultaneously protects the reinforcing steel against corrosion and transmits the force of externally applied loads to the steel. Cracking and subsequent spalling of the cover are the results of volumetric expansion accompanying the corrosion of the underlying steel reinforcement; the strength of the reinforced concrete is reduced where corrosion of the steel reduces the effective cross-sectional area of the reinforcement, and rust stains appear on the surface below or adjacent to the deteriorated area.

As early as 1911 it was shown that cracking of steel-reinforced concrete is caused by electrolytic corrosion of the reinforcement, a depth of cover less than 1/2 in. results in cracking and spalling of the concrete within 3 years of exposure to the atmosphere, and the remedy is to provide sufficient cover over galvanized steel reinforcement.(17)

The thickness of concrete cover needed to protect the steel reinforcement depends on the quality of the concrete and the moisture conditions to which the exterior of the structure is subjected. In a concrete floating

pier the portion that is continuously submerged will have less available oxygen than the upper portion that is exposed to alternate wetting and drying. Also of importance is the fact that the precast structure will be subjected to flexure; if the steel is either very near or at the neutral axis of the horizontal slabs of the pontoon, any bending will produce a series of cracks which facilitate ingress of seawater to the reinforcement.

In reinforced concrete the widths of hair cracks scarcely exceed 0.004 in.(18)

The maximum acceptable crack width at the surface of the concrete cover ranges between 0.004 and 0.012 in. The widths of probable cracks are determined by the tensile stress in the reinforcing steel; this implies the need for limiting the maximum tensile stress as a means of preventing corrosion of the steel. The crack width at the surface of the concrete cover is also related to the thickness of cover; increasing the thickness to increase protection of the steel can produce a wider crack at the outer surface of the cover.(19)

With regard to cracking of the reinforced concrete in a floating pier, the following is considered a guide to the permissible limits: "An assessment of the likely behaviour of a reinforced concrete sea structure in operating environmental conditions should show that the surface width of cracks would not, in general, exceed 0.3 mm (0.01 in.). The assessed surface widths of cracks at points nearest the main reinforcement should not, in general, exceed 0.004 times the nominal cover to the main reinforcement. It should be recognized that in a reinforced concrete structure, under the effects of load and environment, the actual widths of cracks will vary between wide limits and the prediction of an absolute maximum width is not possible. The possibility of some cracks being wider than the above must be accepted unless special precautions are taken."(20)

"A cover as small as 1/2 in. will be sufficient only if the reinforcement is well distributed and the concrete is completely dense, and this can be accomplished only if ... highly efficient vibration is applied."(16)

The general preference is to increase the thickness of cover to ensure more protection for the steel reinforcement against corrosion. However, research has established that crack distribution in the cover is improved and maximum width of cracking is reduced when the cover is decreased.(18)

"The greater the thickness of the cover the more susceptible it is to cracking by bending stresses. (It has been observed) that even 1/2 in. of sound high grade concrete will protect steel from salt water corrosion. ... An extra inch over a large area can add materially to the cost."(21)

Corrosion of Reinforcing Steel

Corrosion of steel is a complex electrochemical action which begins when galvanic cells are created between those portions of reinforced concrete where no corrosion exists (i.e., cathodic pole) and those portions where corrosion is incipient (i.e., anodic pole). Two types of galvanic

cell are possible: (1) dependent on local differences in concentration of oxygen available at the surface of the steel, and (2) dependent on different concentrations of anions (e.g., chloride, carbonate, sulfate). The effect of the electrochemical action is the transfer of iron molecules into solution which, in the presence of oxygen, produces rust (i.e., a brittle coat of hydrated ferrous oxide) on the surface of the reinforcing steel.

The ferrous oxide created as a consequence of corrosion occupies 2.2 times the original volume of the reinforcement, and the pressure resulting from this volume change reaches values as high as 4,700 psi.(22)

Reinforcing steel embedded in portland cement concrete is normally protected against corrosion by the passivating film of ferrous oxide which is produced in the alkaline environment. Penetration of seawater through the concrete cover provides chloride ions which, in association with any oxygen dissolved in the seawater, destroy the passivating film and initiate corrosion of the steel. The amount of oxygen present in seawater within several feet of the aqueous surface averages 5 ml per liter or 0.5% by volume. Thus, corrosion of reinforcing steel is not likely to occur in concrete submerged continuously.

Corrosion of steel embedded in partially dry concrete (e.g., those portions of the floating pontoon exposed to the atmosphere) is the result of transmission of oxygen (in the form of dissolved air) through the water-filled capillaries in the hardened cement paste matrix. Cracks, of course, would facilitate greater supply of oxygen from the atmosphere.

Concrete normally protects steel reinforcement against corrosion. In maritime applications of reinforced concrete, however, it has been well-established that corrosion of the steel requires the presence of oxygen and chlorides in combination with moisture. The probability of corrosion is related to at least eight factors and increases as: (1) the W/C of the concrete increases, (2) the cement content of the mixture decreases, (3) the thickness of concrete cover over the steel decreases, (4) the concentration of chloride ions increases at the interface of the steel and surrounding cementitious material, (5) the supply and penetration of seawater increases, (6) the pH of the hardened cement paste* decreases (from a value of about 12.5 when new) as the result of the continuous effect of carbon dioxide from the atmosphere. (7) the workability of the freshly mixed concrete decreases, and (8) the degree of compaction of the freshly mixed concrete decreases.

Whether or not corrosion of the steel occurs is dependent on whether the pH is below or above a value ranging between 10 and 11; in other words, whether or not calcium hydroxide is present in the matrix surrounding the steel.** If the matrix is alkaline, calcium hydroxide is present in sufficient quantity in the matrix. Carbonation of the cementitious

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* Actually, the pH of water in contact with the hardened cement paste.

** If the pH at the interface between steel and concrete is below a value of 9, the chemical protection (provided by the concrete cover against corrosion of the steel) is destroyed.(13)

matrix causes conversion of calcium hydroxide into calcium carbonate and simultaneous reduction of alkalinity, thus resulting in loss of the protective film around the steel reinforcement. The hydroxl ions in concrete normally passivate the embedded steel. If sufficient chloride ions from the seawater are present, the hydroxl ions cannot maintain the protective film around the steel; and in the presence of water as the electrolyte, the steel corrodes if oxygen is available.

"As soon as chloride ions are in excess over hydroxl ions at the steel surface, the main corrosion product will be ferrous chloride and the hydroxides will be deposited away from the corroding surface. Corrosion is, therefore, not self-stifling. ... Very thin concrete cover over steel may not result in trouble (as the results of exposure to seawater) if the quality of that concrete is extraordinarily high."(23)

The quantity and size of voids under the aggregate particles in the concrete adjacent to the embedded steel are other factors affecting the severity of corrosion. Concrete having a low W/C is comparatively dry when freshly mixed and, unless extra care is taken during placement, larger and more numerous voids are likely adjacent to the steel reinforcement than in the case of a wetter mixture.

In either a floating reinforced concrete pier or landing stage the top and upper sides are exposed to splashing and spray. An accumulation of chlorides occurs in this portion as a result of successive cycles of drying by evaporation. Since this portion of the floating structure is only partially saturated, oxygen diffusion occurs readily. Differential concentrations of oxygen and chloride are created in the free water throughout the concrete, and corrosion of the reinforcing steel is intensified because of these differences in the galvanic cells which are large (macro-cells) in concrete because of the heterogeneity of concrete compared with small galvanic cells (micro-cells) which exist when the steel is surrounded only by the atmosphere. The poles of the macro-cells may be several feet apart. A schematic representation appears in Figure 1.** Thus, the portion exposed to the atmosphere is vulnerable to cracking and subsequent spalling. The submerged portion of the floating structure is saturated, and the oxygen content of seawater being very much lower* than that of the atmosphere, corrosion of reinforcing steel in this portion of the structure is usually absent. In both cases the floating facility is presumably devoid of structural cracks.

Corrosion of steel reinforcement in concrete is a complex subject. An excellent explanation, intended for the engineer rather than the scientist, appears in (25).

The most important factor in preventing corrosion of the reinforcing steel is the degree of contact between the steel and the enveloping dense concrete. If placement of the freshly mixed concrete is incorrect, large voids will exist adjacent to the steel and the chances of corrosion will be increased. Local differences in the permeability of the cementitious cover intermittently exposed to the atmosphere will allow differences in the amounts of seawater, oxygen, and carbon dioxide available at various

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* 5 ml per liter, or 0.5% by volume, near the oceanic surface.

** Copy of Fig. 7 in (24).

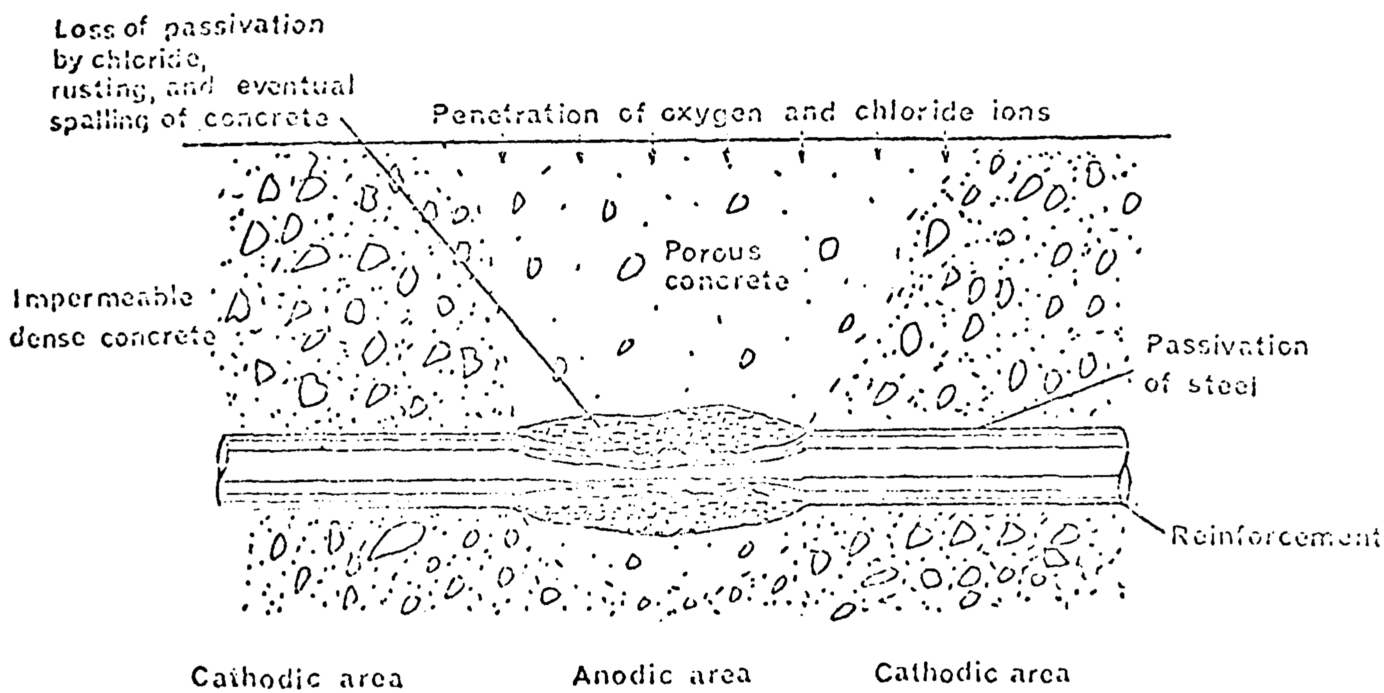

Fig. 1.* Schematic Representation of the Electrolyte Macro-Cell in Reinforced Concrete Causing Spalling

* Source: Figure 7 in (24).

locations along the surfaces of the embedded steel. If the concrete is continuously submerged, as would be the case for the bottom and major portions of the sides of the floating structure, few or no electrolytic cells would be created at such voids adjacent to the steel and any corrosion would be minimal.

Carbonation of Concrete

The amount of calcium hydroxide created during hydration of portland cement is sufficient to form a highly pH protective film around the reinforcing steel. Hydrated portland cement reacts chemically with carbon dioxide which is present in the atmosphere and to a lesser degree in seawater. If the concrete is continuously submerged in seawater, the originally high value of pH will persist mainly because of insufficient carbon dioxide.*

A good explanation of the effects of carbonation is the following excerpt from (26): "One of the products of the combinations between water and cement is calcium hydroxide. If this calcium hydroxide is exposed to carbon dioxide from the air or water surrounding the paste, calcium carbonate is formed. ... Under moist conditions it (carbonation) is of value in protecting marine structures against the corrosive action of seawater, but under dry conditions it may be the major cause of crazing. ... It is important to note that carbonation is appreciable even under the condition of moist storage (in fog), and that under the extreme condition (i.e., drying) the amount of combined carbon dioxide equals 25 per cent of the weight of the cement. Other things being equal, the carbonation is greater for higher water-cement ratios, for longer periods of exposure, for earlier ages of exposure to drying conditions, and for lower humidity of the air. Presumably the carbon dioxide content of the atmosphere would influence the rate and amount of carbonation, but this factor was not studied in the investigation. With regard to exposure to air, the tests were conducted under normal laboratory conditions. It will be borne in mind that these tests were made on relatively small specimens (3/4-in. cylinders), and that in larger masses of concrete the effect of carbonation will be confined largely to the region near the surface. However, this region is of particular importance with regard to surface cracking and weathering; and it (is) believed that increased attention to the role of carbon dioxide in volume change is justified."

Carbonation causes increased drying shrinkage while the hardened paste is exposed to the atmosphere, thus promoting the development of cracks. Carbonation also causes reduced alkalinity of the paste** by neutralizing the calcium hydroxide and thus nullifying the efficacy of the concrete protecting the steel reinforcement.

"Although the atmospheric carbonation of cement products leads to a decomposition of the hydrated cement compounds, the strength is considerably increased. It is evident that the calcium carbonate formed

* In seawater the average content of carbon dioxide is 0.008% by volume whereas in the atmosphere the concentration is 0.03% by volume.

** Resulting in pH values less than 10.

is in itself an excellent cementing medium ... . The rate of absorption of carbon dioxide by cement products is very slow in materials saturated with water. As the water content is reduced by exposure to air at successively lower humidities, the rate of absorption of carbon dioxide becomes increasingly rapid. ... (In a concrete structure) the carbonation is not likely to proceed beyond a surface layer, up to about 1/4 inch thick, and the main body of the material remains unaffected."(27)

Corrosion of reinforcing steel, as a consequence of carbonation in the exposed portions of concrete floating piers, therefore is probable when the protective cover over the steel is only 1/4 in. thick.

PROTECTIVE COATINGS

General

The ACI in concert with the PCA recommended in 1917 (28) that in floating concrete vessels all steel reinforcement should be galvanized and all exterior surfaces of the hardened concrete should be coated with an elastic waterproofing. In 1975, galvanized reinforcement is being used in many marine structures and synthetic flexible protective coatings are not uncommon.

On Reinforcing Steel

Bond of concrete to steel reinforcement is slightly decreased if the steel is zinc-coated. The zinc does not prevent electrolytic action, but the products of corroding zinc "... diffuse through the interstices of the mortar without creating the pressure produced by the corrosion of iron. ... Both zinc and cadmium are electro positive to iron and consequently retard corrosion, whereas metallic coatings which are electro negative are undesirable and are known to accelerate corrosion."(29)

"Due to its wide availability, the cost of galvanized wire fabric is substantially less than that of galvanized reinforcing bars."(30)

"Where special considerations require the concrete cover to be less than 3/4 in., galvanized reinforcment should be provided. ... Concrete cover should be suitably increased or galvanized reinforcement used in extremely corrosive atmospheres or other severe exposures."(31)

Hardened concrete has low tensile strength and is reinforced to overcome this deficiency. Under load the tensile stresses are transmitted to the reinforcing steel via the bond at the interface between concrete and steel. If the reinforcing bars are galvanized as a means of preventing corrosion of the steel, the chemical reaction of the zinc coating with the alkaline cementitious material usually (depending on the type of cement) results in the evolution of hydrogen at the interface at the expense of the zinc; this reaction causes reduced bond between concrete and reinforcement, and also increases the permeability of the concrete cover. Dissolving chromium trioxide in the mixing water so that the concentration is at least 70 ppm has been found effective in preventing evolution of hydrogen at the zinc coating of galvanized steel bars embedded in cement paste.(32)

Protective coatings on the reinforcing steel thus are beneficial in minimizing potential corrosion of the embedded steel. Hot-dip galvanizing, whereby the cage of assembled steel reinforcement is immersed in a bath of molten zinc to provide a coating about 0.020 in. thick, has been successfully used. In contrast, a coating of cadmium can only be applied by electroplating, and the maximum thickness of the plating is about 0.002 in.

"Long-term tests have shown that the initial attack on zinc by the alkalies released during hydration of the cement is not progressive and that the coating can be expected to have good durability. ... This alkalinity ... is corrosive to the zinc coating, forming initially a layer of zinc hydroxide and subsequently a complex calcium zincate compound which is insoluble in the highly alkaline pore liquid in the concrete (cover). The chemical reaction produces a tight bond between the concrete and the zinc-coated steel and provides a barrier against further alkali attack on the underlying zinc. ... The use of galvanized steel diminishes the influence of the very variable physical properties of the concrete cover, ... may permit lower depths (thicknesses) of cover to be used, and provides a hedge against poor workmanship in the compaction of the concrete. Chlorides taken up by the concrete have less effect on galvanized steel than on bare steel and field observations have shown its superiority over bare steel in marine environments. ... Performance so far suggests that these depths of cover (1 in. where designed compressive strength of the concrete is 7250 psi and the concrete is exposed to seawater) could be reduced by 25 percent if the steel is protected by a zinc coating weighing not less than 500 g/m^2 (equivalent to a thickness of 0.003 in.). ... The average ultimate bond strength of galvanized bars is between 3.27 and 3.59 MN/m^2 (475 and 522 psi) compared with 1.31 to 1.59 MN/m^2 (190 to 231 psi) for rust-free bars and 2.90 to 3.10 MN/m^2 (422 to 450 psi) for rusted bars. ... There is evidence that concrete ... retains its bond to the reinforcement longer if the reinforcement is galvanized. ... The reaction between zinc and the alkaline liquid in the pores of freshly placed concrete can form bubbles of hydrogen gas which would have an unfavorable effect on the bond strength in normal reinforced concrete. The quantity of gas generated depends on the alkalinity of the pore solution, on the type and condition of the zinc layer, and, more particularly, on the minor constituents in the cement. It has been observed that small amounts of chromates in the cement, or dipping the galvanized steel in a chromate bath, suppresses the evolution of hydrogen. The concentration of chromates in the pore liquid necessary to inhibit the formation of hydrogen is very low -- of the order of 70 ppm in the cement paste, corresponding to a soluble CrO_3 content of 0.0035 percent (by weight) in the dry cement, assuming a water/cement ratio of 0.5. (Since) some portland cements are low in chromate, chromate-treated galvanized steel should therefore be used with all cements."(33)

Organic coatings (e.g., epoxy resins) on steel reinforcement should be avoided because they prevent passivation of the steel surface by the enveloping concrete and interfere with the bond of concrete to steel.

On Exposed Concrete

As mentioned earlier herein, the joint ACI-PCA committee recommended (28) that elastic waterproofing should be applied to concrete vessels. Discussion of conclusions reached from laboratory tests (34) indicates that hydrated portland cement, in concrete submerged in seawater, is capable of absorbing an appreciable amount of chloride from the seawater. This is especially so at low temperatures ranging between 14° and 0° F. The application of a waterproof material to the exterior surface of the concrete vessel, before immersion in seawater or brine solutions, will prevent penetration of chloride ions into the concrete.

The application of a flexible coating, either neoprene or epoxy, can be expected to protect the precast reinforced concrete floating pier or landing stage against penetration by salt-laden moisture (either in liquid or vapor phase or both). Those portions of the structure exposed to the atmosphere, either continuously or intermittently (alternately wet and dry), likewise can be protected against carbonation and also against migration of oxygen and chloride ions to the embedded steel. The necessary guidance for selecting the correct approach to the problem of applying an effective barrier onto all exposed surfaces of the floating pier is provided by (35).

Note, however, that no protective coating would be necessary for a floating structure made of polymer-cement-concrete* reinforced with either deformed steel bars or steel wire fabric or both. In contrast, a floating structure coated with a film of flexible epoxy resin would undoubtedly necessitate towing the structure into a graving dock for periodic renewals of the protective coating.

OBSERVED EFFICACY OF CONCRETE COVER

General

The thickness of concrete cover, sometimes designated as the depth of cover, is the shortest distance from the external surface of the concrete to the nearest surface of the reinforcing steel (including wire ties).

In a thin structural concrete element the thickness of cover constitutes a large percentage of the total thickness of the element.

Laboratory Test Specimens

At the suggestion of Arsham Amirikian, then Chief Engineer for Structural Design at BuDocks, the first of several investigations on bond efficiency in precast thin-shell reinforced concrete was completed in 1948, as reported in (36). The purpose was to determine the minimum spacing of steel reinforcing bars and the minimum depth of concrete cover

* See p. 5 herein (under Admixtures).

necessary to develop bond of concrete to steel in thin-shell concrete. The 90 bond pull-out test specimens were prismatic in configuration and embedded therein were 1, 2, or 3 parallel bars of reinforcing steel having diameters of either 3/4 or 1 in. Lengths of embedment, which determined the lengths of the concrete prisms were 12, 18, and 24 times the bar diameter. The clear spacing between parallel bars, and the corresponding thickness of concrete cover, were equal to 1-1/4, 1-1/2, and 2 times the maximum size of aggregate which was varied to represent 1/4, 3/8, and 1/2 in. Thickness of cover and spacing of bars was varied from 5/16 to 1 in. Average compressive strengths of the concretes at 7-day ages were 5,000 psi, the W/C always 0.44 by weight, and the A/C varied between 3.6 and 3.7 by weight. ASTM Type III portland cement, crushed limestone as the coarse aggregate, and natural sand were used in fabricating all concrete prisms. Average slumps were 0 in. for 1/4 in. maximum aggregate, 1-1/4 in. for 3/8 in. aggregate, and 2 in. for 1/2 in. aggregate. The concrete batches were air-cured at about 60°F to simulate field practice. Each pull-out test was continued until failure of the thin-shell specimen occurred by splitting of the concrete, compressive failure of the concrete, or the steel bar pulling through the concrete. The test data, which are not conclusive for all precast thin-shell reinforced concretes, show that in the case of these experimental concrete specimens: (1) increasing the depth of cover results in increased bond resistance up to certain limits; (2) as the cover is reduced from 3/4 in. thickness, the ability of the concrete to develop bond decreases with decreasing depths of cover and decreasing spacing of the bars; (3) bond is a function of the tensile strength of the concrete; (4) differences in maximum size of aggregate, within the range from 1/4 to 1/2 in. inclusively, does not influence the bond; and (5) water gain, or the formation of water pockets, develops under reinforcing bars that are horizontal during casting of concrete if the consistency is very stiff, and consequently about 3% of the reinforcing bar surface is not effective in bond.

In 1951, BuDocks authorized further investigation to determine whether or not small spacing between reinforcing bars in thin-shell concrete exerts an adverse effect on bond strength. The results of this investigation are divided into three parts and described in detail in (37), (38), and (39), but a summary of the salient points suffices for the purpose of this report. Part I of the investigation (37) emphasizes the seriousness of splitting stresses caused by the wedging action of the lugs in the reinforcing bars; it shows that bond is sensitive to the spacing between parallel bars, bond strength is increased if supplementary wire fabric is present, and high-strength concrete increases bond as much as 33% (within the limits imposed for thickness of cover, maximum size of aggregate, bar diameters, and clear spacing between bars). Part II shows (38) that low bond strengths are due to splitting regardless of whether the parallel bars are closely or widely spaced. Part III (39) shows that failure of spliced reinforcing bars causes splitting of the concrete, strength of a splice is sensitive to depth of cover, and wire fabric enclosing the splice increases the splice strength appreciably.

Sixty-four concrete test specimens, each 8 in. square by 2-1/2 in. thick and in each of which were embedded 0.0625-in.-diameter (16 gage) wires or 0.1770-in.-diameter (7 gage) wires or 1/4-in.-square cross-sectional deformed bars, were flexurally loaded after 14 days of moist curing so as to produce cracks (at the upper horizontal surface) perpendicular to the direction of reinforcement. By means of the procedure explained in (40), the V-shaped cracks were maintained at various widths ranging from 0.005 to 0.05 in. while the test specimens were exposed for 10 years in the marine atmosphere adjacent to Puget Sound. Examination of the reinforcement, after removal from the specimens, indicated that "development of occasional cracks of fairly large width in sound concrete does not promote serious corrosion of reinforcing steel". The reinforcement was protected by a minimum cover of 1-1/8 in. Though these tests did not reveal the extent of steel corrosion associated with thinner cover, Tremper mentions that steel reinforcement often corrodes sufficiently to crack the concrete if the protective cover is as thin as 1/2 in.

A laboratory investigation of corrosion of 1/4-in.-diameter steel bars embedded in concrete test panels was made for BuDocks.(41) The rectangular concrete panels (6 by 12 in.) were made in three thicknesses (3/4, 1-1/8, and 1-1/2 in.); thicknesses of cover were respectively 1/4, 7/16, and 5/8 in. After curing in 70°F fog for 1 day followed by 70°F air at 50% RH, the panels were subjected to four types of exposure (one of which was 70°F fog) for 1 year. Results indicated six conclusions: (1) rich concrete provides better protection than does lean concrete; (2) wetter concrete, having a slump of about 3 in. when freshly mixed, provides better protection than does drier (stiffer consistency) concrete; (3) the minimum cement content when using 3/8 in. maximum size aggregate is 6 bags per cu yd and the W/C is not greater than 6 gal per bag; (4) coverage as thin as 1/4 in. prevents corrosion for at least 1 year if the freshly mixed concrete is of proper consistency, the mix proportions ensure maximum density, and the fresh concrete is fully compacted; (5) the rate of corrosion decreases as the cover thickness increases up to 1/2 in., but cover thicker than 1/2 in. affects the corrosion rate very little; and (6) alternate wetting and drying is a more severe exposure, at constant temperature, than is continuously wet exposure.

With the view of evaluating single factors (cement content, W/C, consistency, aggregate gradation, and thickness of cover over reinforcement), the eight statements quoted below were established as the result of laboratory tests of 700 salt-free reinforced mortar and concrete prismatic specimens stored either in a standard fog room or outdoors (36° to 108°F and 5% to 95% RH) for periods ranging from 2 weeks to 2 years.(42) The thickness of cover over reinforcing bars, which were 0.24 in. diameter, ranged from 0.39 to 2.36 in. Size of mortar and concrete test specimens ranged from 1.57 by 1.57 by 6.30 in. to 4.72-in. cubes. "(1) A dense cement paste which forms an even coating over the reinforcment is the best protection against corrosion. Both attributes, 'even' and 'dense' are considered equally essential for protection, and any factor influencing these qualities of the cement paste influences ipso facto its protective value. (2) Consistency of mortar and concrete has a most pronounced effect upon the rate of rusting, which is not governed by the water-cement ratio, or cement content. (3) Mortar mixes containing 400 kg cement per cu m

(675 lb per cu yd) and concrete mixes containing 235 kg cement per cu m (396 lb per cu yd), when of plastic consistency and good grading, afford practically complete protection of the reinforcement in a climate similar to that of Israel. (4) Influence of cement content upon rate of rusting should not be overestimated, and the content generally called for by strength requirements appears to be adequate for protection of the reinforcement, provided the concrete is well graded and of plastic consistency. Concretes of dry and of wet consistency provide inadequate protection against corrosion. (5) Although the average quantity of rust on reinforcement embedded in concrete of dry consistency is smaller than that in wet concrete (2.7 as against 5 in the tests), the local decrease of cross-sectional area may be much greater, because of the concentration of rust at breaks in the cement paste covering the reinforcement. (6) Water-cement ratio, known to control principally compressive strength, durability and water tightness of concrete, does not in itself control the rate of corrosion of reinforcement. (7) Preliminary results show that coarser grading of concrete and mortar tends to improve their protective value. Further study of this phenomenon is required. (8) Increasing the depths of covering enhances the protective value of mortars which in themselves do not sufficiently protect the reinforcement. No effect of depth of covering was observed in mortars which, even when very thin, afforded adequate protection of the reinforcement." The test data in (42) prove "that the behavior of steel embedded in mortar is basically the same as when embedded in concrete, though quantitatively the effect is not necessarily identical."

More than 400 mortar test specimens, each dimensionally 1.57 by 1.57 by 6.30 in., were made using either seawater or fresh water. Each specimen was reinforced with a 0.24-in.-diameter steel bar so that the thickness of mortar cover was 0.67 in. The specimens were stored in standard fog, fresh water, or seawater for periods ranging from 3 months to 4 years and when removed from storage were broken open for examination relative to steel corrosion. This series of tests (43) was a sequel to the earlier investigation (42). The measurements of pH necessary to inhibit corrosion of the reinforcement showed that a minimum pH of 11.5 is needed; this value corresponds to that attainable with very workable mortar mixtures, provided the thickness of mortar cover is quite even and very dense. The evenness of the cover was shown to be more important than the density. Reinforcing steel was found practically free of corrosion in specimens continuously stored in either seawater or fresh water, despite the fact that seawater had been used in mixing the mortar; but reinforcing steel in all specimens exposed to humid atmosphere exhibited various degrees of corrosion, the least amount in mortars having a W/C of 0.80 by weight and an A/C of 2 by weight. This indicates that W/C alone does not predetermine the rate of corroding reinforcement; it indicates that the consistency of the cover, when freshly mixed and during placement, is an important parameter relative to the protection afforded to the embedded reinforcing steel. Another important parameter is the A/C; mixtures

relatively rich in cement content are more likely to offer greater protection to the embedded steel than do lean mixtures. The test data in (43) also suggest that coarse gradation (i.e., high fineness modulus) tends to enhance the protectivity of the concrete or mortar enveloping the embedded steel.

Investigation of corrosion of prestressed steel wire (nearly 3/16 in. diameter) in mortar and concrete test specimens shows (44) that chloride is the prime factor in corrosion of the steel. The type of portland cement has practically no influence on degree of corrosion. Whether the mortar is moist-cured in a 73°F atmosphere or at atmospheric pressure in steam at 180°F has very little influence on the degree that prestressing wire will corrode in the presence of chloride. Steel wires were embedded along the longitudinal axes in 1- by 1- by 18-in. mortar prisms and in 2- by 2- by 18-in. concrete prisms. The mortar prisms were stored in 73°F atmosphere at 50% RH, but the central portion of each test specimen was wrapped in a continuously wet towel. Externally applied load was maintained, by means of a heavy steel frame that supported each prism, at 140,000 psi tension on each embedded wire. The mortar prisms were stored in this environment for periods of 1 to 6 months, whereas the storage of the concrete prisms extended through various periods up to 2 years. Examination of the test specimens was accomplished by sawing longitudinal slots along two opposite sides of each prism, splitting open the prism, removing the wires, and visually observing the condition of wire and adjacent cementitious matrix. Severity of corrosion determined visually is often misleading because the observer normally is inclined to associate severe corrosion with large surface area of steel, whereas depth of penetration is the important aspect. Test specimens that did not contain either calcium chloride or sodium chloride in the mix design exhibited no corroded steel wires. Chlorides had been added to the mixing water in amounts of 0%, 2%, and 4% by weight. Note that the chloride content of seawater corresponds to that of a 4% solution of calcium chloride dihydrate ($CaCl_2 \cdot 2H_2O$) which is the common reagent form of calcium chloride. Prisms that were made to contain no chloride showed no corrosion of steel wire and the tensile strengths of such wires were the same as that of the original wire. The test data reveal that steel corrosion is associated with voids that are adjacent to the steel and which have dimensions comparable with the diameter of the steel wire. In the presence of voids, an increase in cover of mortar or concrete from 1/4 to 5/8 in. does not significantly decrease the corrosion of the steel. The data also show that corrosion may occur whether the steel wire is or is not subjected to external load. "The most important factor in preventing corrosion is to provide good bonding of a dense concrete to the wire by adequate placement procedures."(44)

In a 5-year-long program (45) involving 132 concrete test specimens, the effects of 2% calcium chloride additions to dense and porous concretes were determined relative to corrosion of 3/8-in.-diameter steel bars embedded at various depths in the 6-in. concrete cubes. The W/C of the dense concrete was 0.65 while that of the porous concrete was 0.55, both by weight. The values of A/C in each concrete were quite

similar. The porous concrete mixture incorporated a different gradation of aggregate as a means of ensuring comparative porosity. Cover over the steel bars, including their ends, varied; thicknesses of cover were 1/4, 1/2, 1, and 1-1/2 in. Specimens were stored inside and outside the laboratory for 5 years; those indoors were immersed in water so that the embedded reinforcement was vertical; those outdoors were exposed to an average yearly rainfall of 500 hr and to average daily temperatures of 62°F in July and 38°F in January. Regardless of whether stored indoors or outdoors, the chloride ions caused little or no corrosion of embedded steel where the dense cover was 1/2 in. or more in thickness; specimens having 1/4 in. dense cover exhibited corrosion. Specimens stored outside, and in which the cover consisted of porous concrete, showed considerable corrosion even where the cover had been 1-1/2 in. thick. If the diameters of the bars had been less than 3/8 in., the corrosion that conceivably would have occurred would have been sufficiently serious (in reduced cross-section) to constitute structural failure. "In no case could the corrosion be said to have reached serious proportions for reinforcement of 3/8 in. diameter or more ... ." (45)

Prestressed concrete specimens having cracks of various widths were exposed to seawater between high and low tides. Such exposure resulted in no noticeable reduction in either cross-sectional area of the steel (due to corrosion) or tensile strength of the steel after 2-1/2 years in the case of cracks 0.01 in. wide or after 7 years in the case of cracks 0.005 in. wide. "On the other hand, it has become apparent from faults which occurred in ordinary practice that a very small cover (for example, 1/4 in.) is insufficient to protect the steel from corrosion even if the concrete is dense, unless it (the concrete cover) is produced with great care."(46)

Density of the concrete cover is most important and in prestressed concrete reducing the cover thickness to 1/2 in. is permissible and often done.(18)

As the result of an investigation (47) of the effects of spraying the surfaces of reinforced concrete and prestressed concrete test specimens (stored outdoors) once daily with water (containing 3% sodium chloride) for periods of 19 to 24 months, the relationship between thickness of concrete cover (c) and diameter of the reinforcing steel (d) can be expressed as the ratio c/d which is more useful than c alone for indicating the efficacy of the concrete cover. A c/d value ranging between 2.5 and 3.0 appears to indicate adequate concrete cover for protecting the steel against corrosion caused by chloride ions during 2 years of exposure, provided that the W/C of the concrete cover is no greater than 0.49 by weight (5.5 gal per bag). The investigation shows that the surface area of corrosion is decreased by 20% for every 1/2 in. of added concrete cover for thicknesses ranging from 1 to 2 in. Increasing the W/C causes increasing porosity which facilitates penetration of chloride ions and oxygen through the concrete cover. "The larger volume of the rust scale, more than double that of the steel from which it comes, creates splitting stresses on the concrete cover ... . This is one of the main reasons for the longitudinal cracking

of the concrete cover over corroded bars. The resistance which can be provided against such splitting forces depends on the (tensile) strength of the cover ... ." The tensile strength is known to be a function of type of cement, cement content, W/C, and c. The greater the value of d, the greater the expansive force of the rust on a given value of c (e.g., the data show that 1-3/8-in.-diameter bars undergo 4 times more corrosion than do 3/4-in.-diameter bars if c is 2 in.).(47)

Galvanized steel wire fabric reinforcement is used in precast concrete pontoons that serve as the flotation units in floating piers at marinas. "Because of the thin walls, the reinforcement must be kept to a small diameter and placed near the center of the section. For this reason, it adds little to the strength of the section, and its chief value is its ability to diffuse temperature differentials and hold the unit together even if it cracks. Because such cracks frequently heal themselves by hydration of unset cement that is always present in the concrete, the reinforcement serves a useful structural purpose. Some question has been raised as to the possible harmful effect of the reinforcement when close to a surface exposed to sea water, even though galvanized. Proponents of nonreinforcement claim that the water will surely penetrate to the wire, and ultimately will penetrate the galvanizing to start corrosion. However, no corrosion cracks have been detected in any of the otherwise undamaged units in use thus far (through 1964), possibly because the cracking capacity of a corroding reinforcement bar may bear some relationship to its diameter, as well as to its depth of embedment. Test slabs are now (1964) being observed at the Los Angeles Harbor Department Test Laboratory to verify or refute this hypothesis."(48) The test specimens, installed during 1933 under Berth 145, are dimensionally 2 by 12 by 24 in. and are reinforced with galvanized steel wire fabric; some are continuously submerged, some in the tidal zone, and some in the splash zone.(49)(50) As of 1968, no evidence of distress had yet been detected after 35 years of exposure to the saline harbor water.(49) Information regarding the present condition of these so-called test slabs is unavailable.(51)

Actual Structures

The earliest use of a reinforced concrete pontoon appears to be a landing stage in Australia for passengers at a ferry terminal at Sydney in 1914.(52) Its dimensions: 110 ft long, 60 ft wide at one end and 70 ft at the other end, and 7-3/4 ft deep; freeboard of 3-1/2 ft; displacement of 783 tons; 44 watertight compartments; 5-in.-thick sides, bottom, and deck; and 4-in.-thick bulkheads.

The first reinforced concrete scow and the first reinforced concrete barge were constructed about 1917.(53) The concrete cover over reinforcing steel was somewhat less than 1/2 in. in many areas. Examination of both vessels after 22 years of continuous service in the Puget Sound region revealed practically no signs of corroded steel reinforcement; the scow, however, exhibited numerous fine shrinkage cracks. The concrete composing the hulls of both vessels incorporated a high cement factor and a low W/C. Information regarding overall thicknesses of hull and life spans of these vessels is not readily available.

Two floating reinforced concrete landing stages, built in 1918 and launched in 1919 at the Port of Long Beach, are still in operation in 1975. Each pontoon has walls nearly 4 in. thick, comprises three compartments, has a freeboard of 2 ft when loaded to capacity and is 40 ft long, 20 ft wide, and 7 ft high. The reinforcement, which is illustrated in Figure 4 of (54), consists of steel wire fabric in conjunction with steel bars which range in diameter from 1/2 to 3/4 in. The depth of cover approximates 1-1/2 in. To date, these floating structures have required no maintenance.(49) They are presently situated at the 6th Street Ferry Terminal in San Pedro.

The design and construction of the world's longest reinforced concrete pontoon bridge, completed in 1940, is described in (55). Lake Washington Bridge at Seattle includes 25 cellular flat-bottom reinforced concrete pontoons, each 14 ft deep by 59 ft wide and varying from 117 to 378 ft long. The top, side, and bottom slabs are 8 in. thick and inner compartmental reinforced webs are 6 in. thick. Thickness of concrete cover over steel reinforcing bars in the 8-in.-thick outer slabs (top, bottom, and sides) is 1 in. on the exterior and 3/4 in. on the interior. Each pontoon is "essentially a rectangular box girder divided by longitudinal and transverse webs into 12 substantially (14-ft) cubical cells whose sides where subject to transverse load are reinforced as two-way slabs." The pontoons are not subject to alternate freezing and thawing. The fresh water level in the lake fluctuates a maximum of 3 ft.

In 1963 the second floating bridge on Lake Washington was opened to automotive traffic. It is 3 nautical miles from the first floating bridge. The biggest of the 35 prestressed concrete pontoons in the second bridge is 360 ft long, 60 ft wide, and 15 ft high. The weights (in air) of the pontoons range from 4,700 to 6,700 tons.(56)

Construction of reinforced concrete vessels, under the auspices of the U. S. Maritime Commission, began in 1942 and continued throughout World War II. The thinnest hulls were those in 11 barges which had 5-in.-thick bottoms and 4-1/4-in.-thick sides; decks and bulkheads were 4 in. thick. Concrete cover in these barges may be divided into four groups as follows: (1) hull bottoms, 7/8 in. on the exterior and 1/2 in. on the interior; (2) hull sides, 3/4 in. on the exterior and 1/2 in. on the interior; (3) decks, 3/4 in. on the exterior and 1/2 in. on the interior; and (4) bulkheads, 1/2 in. on each side. After several years service no evidence of deterioration, due to corroded reinforcement, is mentioned.(57)

Precast reinforced concrete rectangular cells can serve as framing elements for floating piers.(58) Structural elements 1/2 in. thick require reinforcement consisting of high-tensile (minimum yield strength of 70,000 psi) steel wire fabric which may be supplemented with small-diameter ordinary steel reinforcing bars. Maximum size of aggregate is 1/4 in. Minimum depth of concrete over the wire fabric may vary from 1/4 to 3/8 in., but the structural elements must be cast with a tolerance of 1/32 in. relative to thickness and 1/16 in. relative to overall dimensions. Methods of assembling the cells and the details regarding design of reinforced joints are given in (58).

In 1944 an experimental reinforced concrete LCT (Landing Craft, Tank) was built for BuDocks.(59) The vessel, which duplicated the overall dimensions and the capacity of a steel LCT-6, was 112 ft long and had a 32-ft beam and displacement of 224 tons; source of power was twin diesel engines, propulsion was through two propeller screws, and control through twin rudders. The construction involved precast slabs, precast cells, shotcrete, and cast-in-place concrete.(60) The cells were 4 by 7 by 5 ft in size; wall thicknesses were 3/4 in. for the 4-ft sides and 1-1/2 in. for the 7-ft sides. The slabs were 1-1/4 in. thick. Reinforcement consisted of welded wire fabric in the cells and precast slabs; the bottom and the deck of the vessel were reinforced with wire fabric and steel bars; the sides of the hull consisted of shotcrete reinforced with wire fabric. Maximum size of aggregate was 1/4 in. Maximum dimensional tolerances of shotcrete cover over reinforcement was 1/8 in. The structural design by Arsham Amerikian, then Chief Engineer for Structural Design at BuDocks, provided for a 1-5/8-in.-thick bottom reinforced with 2- by 2-in. wire fabric (No. 3/No. 8) near the bottom of the slab and 2- by 2-in. wire fabric (No. 3/No. 4) near the top of the slab, separated by 1/4-in.-diameter steel bars; 1-1/2-in.-thick bulkheads; and a 1-in.-thick deck. Subtracting the total thickness of reinforcement from the 1-5/8 in. overall thickness of hull bottom, the thickness of concrete cover at the bottom was nearly 1/2 in. The deck was reinforced with 2- by 2-in. wire fabric (No. 8/No. 8) and supported by 2- by 4-in. concrete beams each of which was reinforced with one 5/8-in.-diameter bar near the upper face and one 3/8-in.-diameter bar near the lower face. Though (61) does not include information concerning thickness of concrete cover over reinforcement, Page 72 of (61) indicates that all detailed drawings were prepared by Corbetta Construction Co. (the contractor) and all contract drawings are identifiable as BuDocks Drawings 313648 through 313677. None of these plans were readily available during the literary search made as the basis for this report. The LCT(X) was tested for 6 weeks, during which period the vessel outrode a hurricane, was subjected to the effects of breakers and broaching, and underwent full-speed landings on sandbars and abrasive stony beaches, without damage to the hull. Information regarding the service life of the vessel should be available at NavFac. The steel LCT's have been superseded by LCU's which are 7 to 13 ft longer.

According to the discussion in (60), reinforced concrete barges having hull thicknesses of 1-3/4 in. were built in 1921 and were still in service as late as 1950.

A reinforced concrete barge was built for BuDocks by Corbetta Construction Co. in 1945 after completion of the concrete LCT(X). Length was 106 ft, beam was 30 ft, height was 7 ft, and displacement was 250 tons. This vessel consisted of 112 precast reinforced concrete cells and slabs joined in the same manner as those in the LCT(X). Concrete cover over the bottom reinforcement was 3/8 in., and cover over reinforcement in the deck was 1/4 in. Otherwise, the cover over reinforcement in the walls of the cells was the same as in the cells constituting the LCT(X). Though no report of the construction and final disposition of the barge is available at the NavFac Historian Branch, Public Affairs Division,

CBC Port Hueneme, photostats of BuDocks Drawings 346020 through 346023 (all dated 24 Jun 1944) and Corbetta Construction Co. Drawings DR-1, -2, -4, -6, and Drawing R-1 (all dated between 6 and 26 Jul 1944) were found and served as the source of data described above.

During 1969 in Vietnam 160 reinforced concrete pontoons were built by RMK-BRJ (a combine of American construction companies, namely, Raymond International Inc., Morrison-Kundsen Co., and Brown, Root & Jones) in accordance with a cost-plus-fixed-fee contract, at Cam Ranh Bay and Saigon Island. After having been towed to various sites along rivers emptying into the South China Sea, the pontoons were installed to provide docking and servicing for a variety of surface patrol craft. At each location a number of pontoons are connected to form floating piers; they are held in place by steel pile guides so that the units can move vertically with the tide and also adjust to surface conditions. Each unit is constructed according to a standardized NavFac design. Each pontoon is 8-3/4 ft high, 12-2/3 ft wide, 72-3/4 ft long, and consists of 10 cells. Each end cell is nearly 5 ft long and each of the 8 cells is nearly 7 ft long. Thickness of the top slab is 4-1/2 in., and the sides, bottom, and bulkheads (separating the cells) are each 5 in. thick. The top slab is reinforced with 3/8-in.-diameter steel bars transversely and 1/2-in.-diameter bars longitudinally; the sides and bulkheads, with 3/8-in.-diameter bars horizontally and 1/2-in.-diameter bars vertically; the bottom, with 3/8-in.-diameter bars transversely and 5/8-in.-diameter bars longitudinally. On the basis of these data, the thickness of concrete cover over steel is 2 in. at the bottom, 2-1/6 in. at the sides and bulkheads, and 1-13/16 in. at the top of each pontoon. The W/C of the concrete varied between 4 and 4-1/2 gal per bag (0.36 to 0.40 by weight) and the A/C was 3.0 (by weight) purportedly. (62)

Reinforced concrete barges, for carrying equipment for oil exploration and production, are currently being built at New Orleans by Belden Barges Inc., using precast concrete panels (reinforced with steel wire fabric) as the permanent structural formwork. An outer layer of wire fabric reinforcement is attached to the panels and the assembly is gunned with shotcrete. (63)

When free of live loads, the deck of a floating pier or landing stage is always at a constant height above the surface of the water despite tidal changes; in a stationary pier the deck rests on piles and fluctuations in water level pose safety hazards and inconvenience for relatively small vessels. Concrete pontoons for marinas were first manufactured about 1948.

Prior to 1963 the usual rectangular concrete pontoons used in marinas were cast in modular sizes having deck dimensions ranging from 3 by 6 ft to 8 by 8 ft. vertical dimensions ranging from 14 to 31 in., and wall thickness from 1-1/2 to 2 in. Since then, concrete pontoon production has included units having 8 by 30 ft decks and walls 3 in. thick. Protection of the galvanized steel wire fabric reinforcement against corrosion is afforded by concrete cover that is 1 in. or less thick. The two methods of production are: (1) sides, top, and bottom of the pontoon are cast integrally, and (2) the top of the pontoon is cast separately and joined to the open-top precast box by means of

epoxy resin; the resultant joint is sufficiently strong to obviate extending the wire fabric reinforcement, in the sides of the box, across the joint. In the first method a waterproofed cardboard box, used as the inner form, provides stability during concrete placement by virtue of a grid of cardboard stiffener ribs similar in configuration to those used in egg crates; the cardboard form remains in the completed pontoon. The current trend is to use a solid block of expanded polystyrene instead of the cardboard form. The freeboard of these pontoons is about 1-1/2 ft when subjected to payload.(64)(65)(66).

"Concrete floats have the advantage of inertia under choppy surface conditions, with little reponse to slight changes in pressure. A deck system resting on concrete floats generally gives the impression of greater stability than does a system supported on any other type of flotation in current use. ... Modular concrete float and deck units give promise of low maintenance cost and ease of modification of slip arrangement."(67)

Thousands of nonreinforced and reinforced concrete pontoons (flotation units is the terminology among the manufacturers) are in use at the various marinas situated along the coast of California. As recently as January 1975, Dunham (50) observed that only a few of hundreds of reinforced concrete pontoons at Oceanside showed any deterioration, leakage, or distress due to cracking and spalling despite 10 to 15 years of continuous exposure to seawater. He observed similarly good performance at Newport Beach where the units are nonreinforced and have been subjected for 10 to 15 years to a similar marine environment.

Most if not all of the nonreinforced concrete pontoons have been and currently are being produced as open-top boxes. They are now cast against blocks of foamed polystyrene (commonly known by the proprietary trade name Styrofoam) set within the interior of steel box-like forms; the space between the steel form and the sides and bottom of the polystyrene block is as narrow as 2 in. and in some cases as narrow as 1 in., and the concrete placed therein. At some marinas these floating units are used in an inverted position so that the polystyrene is exposed to seawater at the bottom of the unit. In some instances, (e.g., in the marinas at San Diego, Oceanside, Newport Beach, Marina del Rey, Oxnard Channel Islands Harbor, and Ventura Marina) the open-top units are first covered with precast nonreinforced concrete lids, which are sealed with a mastic to waterproof the joints at the intersections with the four walls, before installation in the upright position. The major producer of nonreinforced concrete flotation units in Southern California is Associated Concrete Products Incorporated which operates casting yards at Costa Mesa and Santa Paula.

After 31 years of exposure to windborne seawater spray from the Pacific Ocean about 200 yd distant, a reinforced concrete bridge was demolished (circa 1967) to allow construction of a wider bridge. Average annual ambient conditions during the 31-year period were: 45°F temperature, 78% RH, and 44 in. precipitation. Examination and tests of 6-in.-diameter cores extracted from the five 48-ft-long beams revealed the following: maximum width of cracking was 0.59 in., average reduction of cross-sectional area of 5/8-in.-diameter steel reinforcing bars due

to corrosion was 17%, average permeability of concrete (142 psi hydrostatic at the upper end of core and atmospheric pressure at the lower end) was $77x10^{-12}$ in. per sec (variations between $14x10^{-12}$ and $153x10^{-12}$ in. per sec), average absorption of water was 5.3% by weight, average sodium chloride content ranged from 0.052% (by weight) in the outer 2 in. of concrete to 0.001% (by weight) at a depth of 6 in. from the exposed surface, and carbonation extended to a depth of at least 0.39 in. The W/C and A/C were not ascertainable and construction records were unavailable; nevertheless, by laboratory analysis the cement content was found to range between 4.0 and 6.2 bags (376 and 583 lb) per cu yd of concrete. Maximum size of aggregate was 1 in. Study of the data (68) indicates that the primary factor in corrosion of the reinforcing steel in the concrete structure exposed to windborne seawater spray (as distinguished from immersion in seawater) is high permeability of concrete, rather than thickness of concrete cover, and the secondary factor is carbonation. The combined effect of both factors allows penetration of chloride ions and oxygen to the surface of the embedded reinforcing steel.

According to (69), centrifugally spun reinforced concrete poles manufactured before 1914 had 1/2-in.-thick concrete covering the steel; this satisfactorily protected the reinforcement for 10 years while exposed to an industrial atmosphere heavily polluted by chemical vapors. Identical poles were manufactured about 1920 and exposed to the same environment; at age 15 years they had not yet exhibited evidence of corroding steel reinforcement. In 1935, accelerated corrosion tests proved that permanently open cracks having a width of 0.012 in. were harmless when occurring in dense concrete typical of that in the concrete poles.

The current British standard specification for reinforced concrete pipe (diameters from 6 to 72 in.) imposes no limit on width of crack although the pipe may be subject to an internal hydrostatic pressure of 20 psi (about 46 ft of head). The allowable absorption of moisture is 6.5% (by weight) after 24 hr immersion. The minimum cover over steel reinforcement is 1/2 in. (70)

In America, reinforced concrete pipe (diameters from 45 to 70 in.) designed for internal hydrostatic pressures not exceeding 125 ft of head (about 54 psi) and having a wall thickness of 2 in. likewise is not subject to a limit on width of crack, and the minimum cover over reinforcing steel is currently 3/4 in. (71)

For the past 30 years in America a concrete cover of about 1/2 in. has been used in the longitudinally prestressed wire-wound prestressed concrete pipe intended for water supply systems. The wall thickness of 2 in. incorporates 12-ft-long steel bars spaced at about 6-in. centers circumferentially before the 36-in.-diameter shell is centrifugally spun. (72) The longitudinal bars are used if internal water pressures greater than 100 psi are expected.

Based on the results obtained with prestressed concrete piles exposed for 13 years to alternate wetting and drying in the tidal range in the harbor area of New York and to alternate freezing and thawing, it appears practical to reduce the thickness of cover over steel to 1/2 in. (73) This limit could apply also to prestressed concrete floating piers.

Prestressed concrete circular tanks, for treatment of sewage and for storage of water, are wire-wrapped circumferentially and protection of the steel wires is by means of a cover of shotcrete. Corrosion of such wires generally does not occur, though hairline cracks often extend through the shotcrete and consequently water from within the tank leaks out. Proper protection of the wires requires a dense mortar cover at least 1/2 in. thick. Experience with such tanks indicates that, where the shotcrete cover is 1/2 in. or more thick and is bonded to the underlying concrete, the wires (after intentional removal of a small area of cover) are bright and clean despite the fact that tanks may have many construction joints through which water has been leaking for as long as 11 years.(74)

Reinforced concrete construction is economical for barges and pontoons having a capacity not greater than 2,000 tons; the amount and total cost of reinforcing steel increase rapidly when this limit is exceeded. Thus, prestressed concrete is preferred in constructing floating vessels of higher capacity and this presents a variety of design problems.(63)

Decisions regarding the structural design of reinforced concrete floating piers involve consideration of various factors (e.g., deteriorative effects of seawater, thermal differentials at the water line, surge, wind force, ice, floating debris, current, tides, wave force, impact of personnel boats or larger vessels, strength of materials, type of concrete, constructional methods, and codes of standard practice.

SPECIFICATIONS FOR DEPTH OF CONCRETE COVER

In an explanation of the design details used during World War I by the Concrete Ship Section of the Emergency Fleet Corporation at Philadelphia (75), it is emphasized that the concrete cover over steel reinforcement be minimized to reduce dead weight. The thickness of cover in concrete vessels designed by the Emergency Fleet Corporation was 3/8 in. which compared favorably with the 1 cm (0.39 in.) used in foreign practice during that period.

The following has been proposed as part of specifications for precast concrete construction. "Contrary to prevailing concept, the thickness of concrete alone is not a true measure of protection against corrosion. The quality of concrete surrounding the reinforcing is of much more importance than its thickness. A very thin layer of rich concrete (containing, say, 7 to 8 sacks of cement per cu yd) properly graded, placed under controlled conditions and vibrated, would provide a cover impervious to moisture. Navy experience with precast concrete structures indicates that the thickness of protective cover could be reduced to as little as 1/4 in. ... For surfaces exposed to weather ... or in contact with water: Main reinforcing in beams ... shall be protected with concrete equal in thickness to two times the maximum size of the coarse aggregate, but in no case shall the thickness of covering be less than 1/2 in. Reinforcing of slabs and secondary reinforcing in beams ... shall be protected with concrete equal in thickness to one and one-half times the maximum size of the coarse aggregate, but in no case shall the thickness of covering be less than 3/8 in."(76)

Another proposal has been made (77) for an acceptability clause in specifications for precast reinforced concrete construction. Amirikian recommends the use of welded wire fabric of small mesh (not over 2 in. square) in thin panels and cellular framing, rather than the use of ordinary reinforcing. Hair cracks are unavoidable and harmless and penetrate only partially through the sectional depth; in concrete floating structures, hair cracks tend to heal or seal when exposed to water, and usually remain impervious in subsequent exposure to water. "Under additional strain (due to improper handling), a hair crack of partial penetration may extend through the whole depth of a casting and thus become a through crack (fracture or cleavage crack, i.e., not over 0.01 in. wide). ... The structural adequacy of the casting will remain unimpaired as long as corrosion of the reinforcement is prevented." Fractures not exceeding a width of 0.01 in. are acceptable in precast concrete provided the reinforcement has been treated with a protective coating (e.g., hot-dip galvanization) before insertion in the molds or forms.

Limits of maximum size of aggregate, thickness of cover over steel, amounts of entrained air, W/C, and cement content for the design and construction of thin precast reinforced concrete elements are stated in (78). Maximum size of aggregate should be no larger than 1/3 of the narrowest dimension of the structural element or 2/3 of the minimum distance between parallel reinforcing bars. Welded wire fabric (2 in. mesh openings) should be used as reinforcement in wide elements having an overall thickness of 3 in. or less. The minimum distance between parallel reinforcing bars should be at least 1-1/2 times the maximum size of aggregate. Steel reinforcement in slabs should be protected, against corrosion, by at least a 3/8-in.-thick cover of concrete. For 3/8 in. maximum size aggregate, the amount of entrained air should approximate 8%; and for 1/4 in. maximum, 9%. Assuming that the compressive strength of air-entrained concrete at age 28 days is 5,000 psi, if the maximum size of aggregate is 3/8 in., the maximum W/C and the minimum cement factor should be respectively 5.75 gal per bag and 6.75 bags per cu yd; if the maximum size of aggregate is 1/4 in., 5.75 gal per bag and 7.4 bags per cu yd of concrete.

The following is a good explanation of minimum cover: "In all these cases (structural elements thinner than 4 in.) a safe minimum coverage can be established by specifying that it should be at least 1-1/2 times or, if possible, twice as thick as the size of the largest aggregate (particle) in the concrete. Though this might make it necessary in some instances to limit the maximum size of aggregate, it can readily be seen that if the coverage is only as thick as the largest aggregate (particle), all the spots where one of these pieces would lodge itself over the steel would be dangerous points of attack. And the place where this is most likely to happen is on the underside of members between the forms and the reinforcing steel."(79)

"The maximum size of coarse aggregate that can be used depends on the size and shape of the concrete members and on the amount and distribution of reinforcing steel. Generally, the maximum size should not exceed one-fifth the minimum dimension of the member, nor three-fourths the clear space between reinforcing bars or between reinforcement and the forms."(65)

ACI Standard 525-63, which appears in (80), emphasizes the need for precision in fabricating thin-section precast reinforced concrete units, whether or not the units are exposed to seawater. The spacing of reinforcing bars and the depth of concrete cover are made a function of the maximum size of aggregate. The nominal maximum size of aggregate must be no larger than 2/3 of the minimum clear space between parallel reinforcing bars or between the wires of the welded-wire fabric which must have mesh not larger than 2 in. square openings. The minimum clear distance between parallel bars must be not less than 1-1/2 times the nominal maximum size of the aggregate. Reinforcement in slabs must be protected with a concrete cover not less than 3/8 in. thick, except that beams and girders must have a cover at least 1/2 in. thick. Welded wire fabric and reinforcing bars must be bent as necessary, secured, and preassembled into cages before insertion in the forms. Each assembly of reinforcement must be placed within a tolerance of +0 in. or -1/8 in. from the nearer concrete face, and must not encroach on the specified minimum cover. Structural units exposed to water must incorporate concrete having a compressive strength of at least 5,000 psi at age 28 days. If the units are subject to freezing and thawing the concrete must be air-entrained; the air content depends on the nominal maximum size of aggregate, ranging from 9 ± 1½% (by volume of concrete) for 1/4 in. maximum aggregate to 7 ± 1½% (by volume) for 1/2 in. maximum aggregate. The W/C must be no greater than 0.38 (by weight) in air-entrained concrete whether the maximum aggregate size is as small as 1/4 in. or as large as 3/4 in. For non-air-entrained concrete the W/C must be no greater than 0.44 (by weight) whether the maximum aggregate is as small as 1/4 in. or as large as 3/4 in. The cement may be ASTM Type II (moderate sulfate-resistant); the specified cement content varies with the nominal maximum size of aggregate and also depends on whether or not entrained air is necessary (e.g., if 3/8 in. maximum size aggregate is used, the cement factor must be 8.25 bags in non-air-entrained concrete and 8.75 bags in air-entrained concrete).

According to the BSI Code of Practice 110 (81), the nominal thickness of concrete covering the reinforcing steel must be at least equal to the diameter of the steel bar. If the reinforced concrete contains 3/8 in. nominal maximum size aggregate and is exposed to seawater, the cement content must be not less than 691 lb per cu yd (equivalent to 410 kg per cubic meter) or 7.3 bags. For reinforced concrete exposed to seawater, the permissible width of surface crack at locations nearest the main reinforcement must not generally exceed 0.004 times the depth of concrete covering the main reinforcement; the code emphasizes, however, that prediction of an absolute maximum width of crack is impossible.

The FIP recommendations (20) are "based on engineering design practices which have evolved during the development of marine structures for both civil and military uses and, in particular, during the development of structures for the exploitation of offshore oil and gas resources." These include precast floating structures which have positive buoyancy and are intended to serve at one location although they may be towed to other locations. (20) indicates that concrete

exposed to seawater and spray must have a compressive strength at age 28 days not less than 40 N per sq mm (equivalent to 5,820 psi), but where severe scouring occurs this limitation must be raised to 45 N per sq mm (6,530 psi). The W/C must be less than 0.45 by weight and preferably less than 0.40 (subject to acceptable workability). "Cement contents in excess of 550 kg per cu meter (equivalent to 927 lb per cu yd or 9.9 bags) should not be used unless special consideration has been given to the increased risk of cracking due to drying shrinkage in thin sections ... ." Since the concrete must be as impervious as possible, "... all design and detailing should be such as to make it easy for concrete to be compacted around reinforcement and into corners of molds and forms. ... Construction and supervision must be such as to ensure a consistently high standard of workmanship." The FIP recommendations concerning thickness of concrete covering steel reinforcement are applicable to floating structures wherein the minimum structural dimension is appreciably greater than the 2-in. limitation imposed by thin-wall precast units; nevertheless, the recommendations point out that those portions of a reinforced concrete structure in a marine environment exposed to intermittent wetting and drying are most susceptible to corrosion of embedded steel, and that in the submerged zone any corrosion of steel reinforcement poses no severe problem.

The CRSI specification (82) that "In no case shall reinforcement be within one bar diameter of the surface of the concrete ..." applies to slabs exposed to the weather. This requirement is similar to that promulgated by the BSI (81).

CONCLUSIONS

If one sets (1) a minimum functional life (i.e., a span of satisfactory performance) for a floating reinforced concrete pier or landing stage composed of an assembly of hollow structural units having an overall wall thickness of 2 in. or less, and (2) a minimum percent of probability that corrosion of the steel reinforcement will not occur during such functional life, it is still impossible to state unequivocally that a specific depth of concrete cover is positively adequate to prevent corrosion of the embedded steel during the functional life of the floating structure. Among many unpredictable factors affecting the functional lives of mass-produced floating piers are geographic location and corresponding climate, amount of exposure to seawater spray, frequency of cyclic wetting-drying or freezing-thawing or both, impact of carelessly applied live loads, and efficacy of protective coating on the exterior of the floating facility. Notwithstanding those influences that are detrimental to the expected functional life, study and subsequent assessment of the technical facts gleaned from the cited literature leads to the conclusions listed below.

1. The minimum depth of concrete cover needed to protect the steel reinforcement against corrosion in precast thin-wall structural concrete subject to marine exposure is a function of: (a) type of

portland cement, (b) cement factor, (c) water/cement ratio, (d) type of aggregate, (e) maximum size of aggregate, (f) aggregate/cement ratio, (g) amount of sodium benzoate added to the fresh water used in mixing the concrete, (h) presence of water-reducing admixture, (i) amount of entrained air, (j) workability of the freshly mixed concrete, (k) degree of compaction during placement of the concrete, (l) watertightness of the hardened concrete, (m) concrete-cover/steel-diameter ratio, (n) size of mesh in wire fabric, (o) spacing of parallel deformed bars, (p) thickness of zinc coating on steel reinforcement, (q) degree of precision in fabricating the precast reinforced concrete structural units, (r) compressive strength of the concrete at age 28 days, and (s) type and thickness of the protective flexible coating applied to the exterior of the finally assembled structure.

2. Steel reinforcement should be designed so that any cracking that may occur in the concrete cover consists of many narrow cracks (micro cracks) rather than a few wide ones (macro cracks). This can be accomplished by installing welded wire fabric together with a relatively large number of small diameter bars rather than only a few large diameter bars. Nevertheless, the reinforcement should not be so congested that proper placement and compaction of the freshly mixed concrete is impractical.

3. A protective coating of zinc on the steel reinforcement is beneficial in preventing or at least minimizing corrosion of the embedded steel. All preassembled reinforcement for each structural unit should be dipped in molten zinc (to ensure a satisfactory galvanized coating which obviates any incipient corrosion cells on the steel) and then should be dipped in a chromate bath (to suppress any evolution of hydrogen after the steel is encased in concrete) before the steel assembly is installed in the forms or molds.

4. A suitably thick coating of water-resistant flexible epoxy resin (a dry-film thickness of 0.012 in., or 12 mils, is considered suitable) is applied to all exterior surfaces in the final assembly of joined precast reinforced concrete structural units to prevent penetration of seawater into any portion of the reinforced concrete structure. Periodic renewal of such protective coating is necessary in all probability.

5. A minimum concrete cover of 5/8 in. is only acceptable if the design specifications require strict observance of the following limitations.

> 5a. The portland cement is either ASTM Type V (preferably) or ASTM Type II. The cement factor is not less than 752 lb (8 bags) in non-air-entrained concrete and not more than 846 lb (9 bags) in air-entrained concrete.
>
> 5b. Nonreactive coarse aggregate consists of crushed and washed (in fresh water) trap rock. Nonreactive fine aggregate consists of washed (in fresh water) siliceous sand. The maximum size of coarse aggregate is not greater than

that passing the 3/8-in. U. S. Standard Sieve, and 100% of the coarse aggregate is retained on the No. 8 U. S. Standard Sieve. The maximum size of fine aggregate is not greater than that passing the No. 4 U. S. Standard Sieve. The combined fineness modulus of the aggregate is not greater than 3.90, and the aggregate/cement ratio ranges between 2 and 3 by weight.

5c. A corrosion inhibitor, consisting of 2% (by weight) sodium benzoate, is added to the potable fresh water used in mixing the concrete.

5d. Depending on the amount of water-reducing admixture present in the mixture, the net water/cement ratio is not greater than 0.40 by weight in non-air-entrained concrete and not greater than 0.35 by weight in air-entrained concrete.

5e. The amount of entrained air in the concrete is not greater than 8 ± 1% by volume.

5f. The slump is not greater than 3 in., and full compaction is obtained by means of vibration.

5g. All cast concrete is cured at 70 ± 5°F, in either fresh water fog or in lime-saturated fresh water that is not circulating or moving, for not less than 14 days. Curing begins immediately after the form or mold is stripped from the structural unit. Every precaution is taken to prevent evaporation of moisture from the concrete after casting and before stripping of the form or mold. The composition of the release agent applied to the interiors of the forms or molds does not interfere with the bond of either (1) the concrete that is used in joining the assembly of precast reinforced concrete structural units or (2) the elastomeric epoxy resin coating that is applied to the completed assembly before exposure to seawater.

5h. The compressive strength of the moist-cured concrete, whether or not air-entrained, is not less than 6,000 psi at age 28 days.

5i. The widths of surface cracks that possibly may develop directly opposite any reinforcing steel (in precast units) are not greater than 0.002 in.

5j. The nominal diameter of deformed ordinary steel reinforcing bars is 1/4 in. so that the c/d (concrete-cover/steel-diameter) ratio is never less than 2.5.

5k. High-tensile-strength (minimum yield strength of 70,000 psi) steel is used in the welded wire fabric that has mesh openings 2 in. square. The wire is not heavier than U. S. Standard Wire Gage No. 4 which approximates a diameter of 0.23 in.

5l. All steel reinforcement is installed within a design tolerance of ± 1/16 in. from the nearest face of concrete.

5m. The minimum clear distance between parallel reinforcing bars is 5/8 in.

5n. Each cage of preassembled steel reinforcement, consisting of welded wire fabric or reinforcing bars or both, is coated (by hot-dipping) with an average of 2.3 oz zinc per sq ft of surface area (nearly 4 mils of coating) followed by dipping in a chromate bath wherein the soluble chromium trioxide content is not less than 0.0035% by weight of the portland cement present in the structural unit.

RECOMMENDATIONS

The approach to this study was shown in the 1 November 1974 edition of Form DD 1498 (Research and Technology Work Unit Summary). Part of the approach required a recommended testing program if the study revealed insufficient information for attaining the objective.

In view of the conclusions established herein, no further effort is considered necessary to determine the minimum depth of concrete cover as acceptable protection of steel reinforcement against corrosion in precast thin-wall structural concrete not thicker than 2 in. overall. Stated briefly, a testing program is considered unnecessary and accordingly is not recommended.

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